

# Single Transverse Spin Asymmetries for Semi-inclusive Pion Production in DIS\*

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**Abstract:** We present a phenomenological approach to the description of single transverse spin asymmetries (STSA) in inclusive hadron production. It generalizes the pQCD formalism for high energies and large  $p_T$  inclusive hadron production processes,  $AB \rightarrow CX$ , by incorporating quark intrinsic motion in the spin dependent quark distribution and fragmentation functions. We concentrate here on spin and  $\mathbf{k}_\perp$  effects in the fragmentation process of a polarized quark into the observed hadron, and give predictions for STSA in semi-inclusive deep inelastic scattering,  $\ell p^\uparrow \rightarrow \pi X$  and  $\gamma^* p^\uparrow \rightarrow \pi X$ .

Polarized inclusive hadron production processes at high energies and  $p_T$ ,  $A, S_A + B, S_B \rightarrow CX$ , can be described in the formalism of perturbative QCD (pQCD), by using the factorization theorem at leading twist; the corresponding cross section reads

$$\frac{E_C d^3\sigma^{A,S_A+B,S_B \rightarrow C+X}}{d^3\mathbf{p}_C} = \sum_{a,b,c,d;\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 z \hat{s}^2} \rho_{\lambda_a, \lambda'_a}^{a/A, S_A} f_{a/A}(x_a) \rho_{\lambda_b, \lambda'_b}^{b/B, S_B} f_{b/B}(x_b) \times \hat{M}_{\lambda_c, \lambda_d; \lambda_a, \lambda_b} \hat{M}_{\lambda'_c, \lambda'_d; \lambda'_a, \lambda'_b}^* D_{\lambda_c, \lambda_c}^{\lambda_c, \lambda_c}(z), \quad (1)$$

where  $S_A$  and  $S_B$  specify the polarization of the initial hadrons,  $\{\lambda\}$  indicates summation over all helicity indices, and the remaining notation should be self-explanatory. We will consider here the case of STSA,  $A_N = (d\sigma^\uparrow - d\sigma^\downarrow)/(d\sigma^\uparrow + d\sigma^\downarrow)$ , which involves Eq. (1) for  $S_A = \uparrow, \downarrow$  and unpolarized hadron  $B$ ;  $\uparrow, \downarrow$  refer to spin orientations perpendicular to the scattering plane ( $\uparrow, \downarrow = \pm \mathbf{p}_A \times \mathbf{p}_C / |\mathbf{p}_A \times \mathbf{p}_C|$ ).

It is however well known that pQCD formalism at leading twist predicts vanishing STSA, in contrast to recent experimental results for  $p^\uparrow(\bar{p}^\uparrow)p \rightarrow \pi X$  at moderately large c.m. energies and  $p_T$  [1]. In the last years, thus, a lot of theoretical work has been devoted to reconcile

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pQCD predictions on STSA with experimental results, by extending the theoretical formalism to include higher-twist effects, which can play a relevant role in the range of  $p_T$  values probed at present. In particular, possible origins of STSA can be introduced by considering intrinsic, transverse momentum ( $\mathbf{k}_\perp$ ), effects in the spin-dependent quark distribution [2] and fragmentation [3] functions. Following this program, in a series of papers [4, 5] we have developed a consistent phenomenological approach, assuming that the pQCD, factorization scheme of Eq. (1) holds also when intrinsic parton motion is included. This way one finds from Eq. (1), at leading order in  $\mathbf{k}_\perp$ , e.g. in the  $p^\dagger p \rightarrow \pi X$  process:

$$\begin{aligned}
\frac{E_\pi d^3\sigma^\uparrow}{d^3\mathbf{p}_\pi} - \frac{E_\pi d^3\sigma^\downarrow}{d^3\mathbf{p}_\pi} &= 2 d\sigma^{unp} A_N(p^\dagger p \rightarrow \pi X) = \sum_{a,b,c,d} \int \frac{dx_a dx_b}{\pi z} \\
&\times \left\{ \int d^2\mathbf{k}_\perp \Delta^N f_{a/p^\dagger}(x_a, \mathbf{k}_\perp) f_{b/p}(x_b) \frac{d\hat{\sigma}}{d\hat{t}}(x_a, x_b, \mathbf{k}_\perp) D_{\pi/c}(z) \right. \\
&+ \int d^2\mathbf{k}'_\perp h_1^{a/p}(x_a) \Delta^N f_{b^\dagger/p}(x_b, \mathbf{k}'_\perp) \Delta'_{NN}\hat{\sigma}(x_a, x_b, \mathbf{k}'_\perp) D_{\pi/c}(z) \\
&\left. + \int d^2\mathbf{k}''_\perp h_1^{a/p}(x_a) f_{b/p}(x_b) \Delta_{NN}\hat{\sigma}(x_a, x_b, \mathbf{k}''_\perp) \Delta^N D_{\pi/c}(z, \mathbf{k}''_\perp) \right\} \quad (2)
\end{aligned}$$

where the first two terms in brackets (respectively the so-called Sivers effect [2] and the contribution recently proposed by Boer [6]) account for  $\mathbf{k}_\perp$  effects in the quark distributions inside the initial hadrons while the last term corresponds to the so-called Collins effect [3]. The new, unknown,  $\mathbf{k}_\perp$  and spin dependent functions of Eq. (2) have a simple partonic interpretation as follows:  $\Delta^N f_{q/p^\dagger}(x, \mathbf{k}_\perp) = \hat{f}_{q/p^\dagger}(x, \mathbf{k}_\perp) - \hat{f}_{q/p^\downarrow}(x, \mathbf{k}_\perp)$ ;  $\Delta^N f_{q^\dagger/p}(x, \mathbf{k}_\perp) = \hat{f}_{q^\dagger/p}(x, \mathbf{k}_\perp) - \hat{f}_{q^\downarrow/p}(x, \mathbf{k}_\perp)$ ;  $\Delta^N D_{h/q}(z, \mathbf{k}_\perp) = \hat{D}_{h/q^\dagger}(z, \mathbf{k}_\perp) - \hat{D}_{h/q^\downarrow}(z, \mathbf{k}_\perp)$ .

The other quantities appearing in Eq. (2), apart from the unpolarized quark distribution and fragmentation functions,  $f$  and  $D$ , are the transverse spin content of the proton,  $h_1^{q/p} = f_{q^\dagger/p^\dagger}(x) - f_{q^\downarrow/p^\dagger}(x)$ , and the elementary double spin asymmetries, computable in pQCD:  $\Delta_{NN}\hat{\sigma} = d\hat{\sigma}^{a^\dagger b \rightarrow c^\dagger d}/d\hat{t} - d\hat{\sigma}^{a^\dagger b \rightarrow c^\downarrow d}/d\hat{t}$ ;  $\Delta'_{NN}\hat{\sigma} = d\hat{\sigma}^{a^\dagger b^\dagger \rightarrow cd}/d\hat{t} - d\hat{\sigma}^{a^\dagger b^\downarrow \rightarrow cd}/d\hat{t}$ .

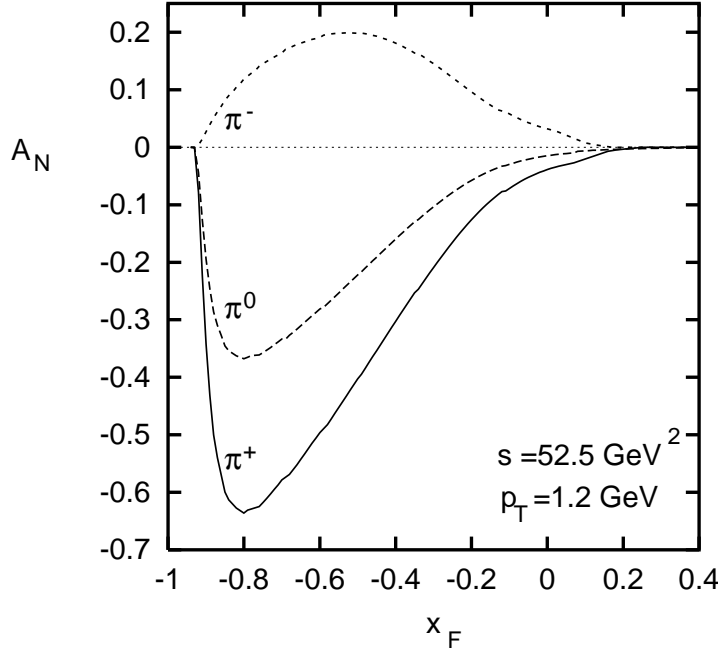
Notice that the new distributions  $\Delta^N f_{q/p^\dagger}$  and  $\Delta^N f_{q^\dagger/p}$  are T-odd functions. In order not to vanish they require some initial-state interactions (with possible breaking of factorization theorem and universality), or finite-size effects in the proton, or spin-isospin interactions.

Eq. (2) may be used to obtain information on the new,  $\mathbf{k}_\perp$ -dependent distributions, by fitting experimental data on STSA in inclusive hadron production. This program has been started and developed in [4], where Sivers effect was considered as the only possible source for STSA, and continued in [5], where a similar study was performed in the case of Collins effect alone. It was shown that both effects are separately able to reproduce well the experimental data on  $p^\dagger p \rightarrow \pi X$ . However, Collins effect alone appears to have some problems, since a reasonable fit is obtained only at the price of saturating the natural positivity bound  $|\Delta^N D_{\pi/q}(z)| \leq 2D_{\pi/q}(z)$  at large  $z$  values. The Soffer's inequality for the transversity distribution,  $2|h_1^{q/p}(x)| \leq q(x) + \Delta q(x)$ , could also be violated by the parametrization of the fit<sup>1</sup>.

Using the information on  $\Delta^N D_{h/q}(z, \mathbf{k}_\perp)$  obtained in [5], we apply here our approach to give predictions for STSA in the semi-inclusive pion production in DIS. These processes are particularly interesting because we expect that, since Sivers effect requires initial state interactions

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<sup>1</sup>We are grateful to E. Leader for drawing our attention on this point.



**Fig. 1:**  $A_N(\ell p^\dagger \rightarrow \pi X)$  for typical HERMES kinematics.

which are suppressed by  $\alpha_{em}$  in  $\ell p$  interactions, Collins effect should be entirely responsible for STSA. An experimental study of these processes should then be very useful for testing the relevance of Collins effect in explaining STSA. A more detailed treatment can be found in [7].

We first consider the process  $\ell p^\dagger \rightarrow \pi X$ . If Collins effect is the dominant effect responsible for the sizeable STSA observed in the analogous process  $p^\dagger p \rightarrow \pi X$ , we expect large asymmetries in this case too. Using Eq. (2), we get

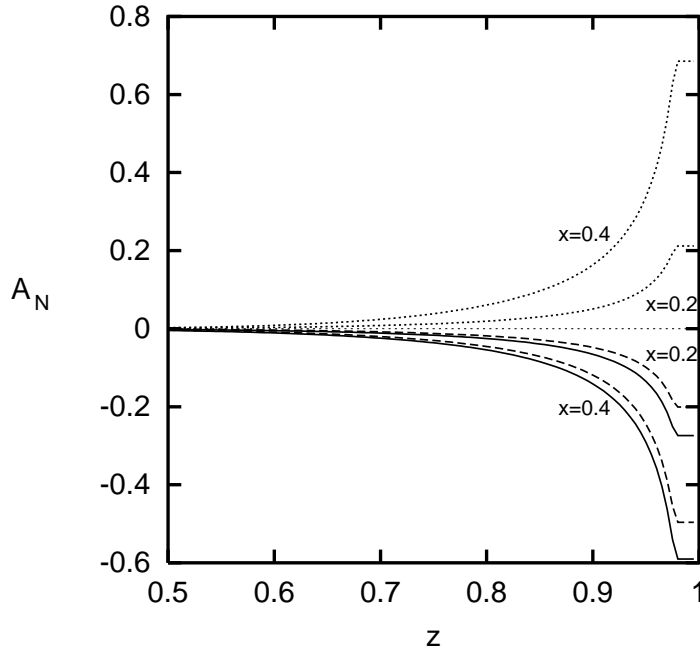
$$2 \, d\sigma^{unp} \, A_N(\ell p^\dagger \rightarrow \pi X) = \sum_q \int \frac{dx}{\pi z} \int d^2 \mathbf{k}_\perp \left[ h_1^{q/p}(x) \, \Delta_{NN} \hat{\sigma}^q(x, \mathbf{k}_\perp) \, \Delta^N D_{\pi/q}(z, \mathbf{k}_\perp) \right] \quad (3)$$

where  $\Delta_{NN} \hat{\sigma}^q = d\hat{\sigma}^{\ell q^\dagger \rightarrow \ell q^\dagger} / d\hat{t} - d\hat{\sigma}^{\ell q^\dagger \rightarrow \ell q^\perp} / d\hat{t}$ .

As an example, in Fig. 1 the STSA  $A_N(\ell p^\dagger \rightarrow \pi X)$  is shown for typical HERMES kinematics, as a function of  $x_F$ . Similar results hold for different kinematical situations corresponding to other available experimental set-ups [7].

A measurement of STSA in  $\ell p^\dagger \rightarrow \pi X$  requires transversely polarized nucleons, which are presently available only for some experiments. However, STSA may be measurable also in the case of longitudinally polarized nucleons, provided one looks at the double inclusive process,  $\ell p^\dagger \rightarrow \ell \pi X$  from which one can reconstruct the  $\gamma^* p^\dagger \rightarrow \pi X$  reaction, which, in general, occurs in a plane different from the  $\ell - \ell'$  plane where the longitudinal nucleon spin lies. In this case one has (see [7] for details):

$$\frac{d\sigma^{\gamma^* p^\dagger \rightarrow \pi X}}{dx \, dQ^2 \, dz \, d^2 p_T} - \frac{d\sigma^{\gamma^* p^\perp \rightarrow \pi X}}{dx \, dQ^2 \, dz \, d^2 p_T} = \sum_q h_1^{q/p^\dagger} \left[ \frac{d\hat{\sigma}^{\gamma^* q^\dagger \rightarrow q^\dagger}}{dQ^2} - \frac{d\hat{\sigma}^{\gamma^* q^\dagger \rightarrow q^\perp}}{dQ^2} \right] \Delta^N D_{\pi/q}(p_T). \quad (4)$$



**Fig. 2:**  $A_N(\gamma^* p^\dagger \rightarrow \pi X)$ :  $s = 52.5 \text{ GeV}^2$ ,  $Q^2 = 8 \text{ GeV}^2$ ; solid, dashed and dotted line refer respectively to  $\pi^+$ ,  $\pi^0$  and  $\pi^-$ .

In Fig. 2 we show  $A_N$  at the same energy values of Fig. 1, as a function of  $z$ : it is large also in this case, although only at very large  $z$  values which might be difficult to reach experimentally.

In conclusion, let us remark that semi-inclusive hadron production in DIS may be crucial for testing the relevance of Collins effect in explaining sizeable STSA. In this context, HERMES and future planned spin experiments at HERA can surely play a fundamental role.

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